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50. Internationales Wissenschaftliches Kolloquium
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Valuation of the heat stress conditions of metals

ABSTRACT

In this paper we give a proposal for a new procedure of valuation of metal materials used for cyclically heat stressed. According to this procedure it will become possible in great extend to replace the long-term tests directly in operation, by laboratory tests, which are going to accelerate the research and development of new materials. The material for our searches we have chosen overlay material for the hot working rolls.

Working conditions of hot working rolls and their influence on materials of rolls

Hot working rolls work in complicated states of stress, which are caused by residual, connection, compression, bending and heat stress, as well as torsion moments. During rolling the heating (from rolled material, from plastic deformation and friction) and cooling are cyclically repeated, which cause stress and strains to the surface layers. By hot working rolls there are two main types of stress – heat and mechanical stress – of which the heat stress is of primary importance.

By working the roll temperature is increasing up to steady regime where the temperature of the roll remains unchanged. The outside layer plastically deformed under permanent heating and cooling processes, which leads to deformability exhaustion, the strength is increasing up to the ultimate strength breaking and it comes to a critical state for tearing – thermal fatigue. The maximum and minimum temperatures determine the stress intensity, which caused the stress; therefore it is necessary to take this fact into consideration in hereby-proposed experiments procedure.

Result of thermal fatigue is damage to the roll surface with cracks and various cavities. With regard to the connection between the thermal fatigue and low – cycle fatigue we have formed generally valid failure principles by thermal fatigue according to Manson's – Coffin's formula

$$\Delta\varepsilon_p N_F^{\alpha} = C \qquad [1]$$

where $\Delta\varepsilon_p$ means repeated plastic strain,
N_F - critical number of cycles
α - constant (0,5 – 0,7)
C - material constant.

C - can be figured out, but it is immensely difficult to determine $\Delta\varepsilon_p$, therefore this value is stated experimentally. The main aim of the work, described in this article, is to propose a procedure for determination of the value N_F in overlay materials of rolls, and the impact of various working conditions on the aforementioned value.

Heat stress parameters and simulation of heating cycles

Factors that must be observed by simulating the operation of hot working rolls, are following:

- Heating temperature,
- Temperature surges frequency,
- Cooling temperature.

Data about the operation temperature in surface layers of rolls are varying from each other and find themselves within the range of temperatures from 500 to 800 °C. The lower temperature limit is usually 80 °C [1]. For experimentation, in frames of heating simulation, the temperatures were determined on base of these figures, as follows:

80 °C – cooling temperature,
750 °C – eating temperature.

The frequency of temperature shocks depends on rolling speed and on the diameter of the roll, so it is proportional to its revolutions. For experimentation we have chosen parameters of the finishing line of the hot wide train of rolls with rolls diameters of 700 mm. As a result of roll diameter and rolling speed we figured out the maximum frequency f =5 Hz.

Nowadays, there are perfect devices, which simulate the processes of temperature changes. Those are intended to simulate the heating – strain cycles of longer duration (minimum heating time is 4s). The frequency of the working cycle by these devices is 10^2 times lower than it is by newer rolling stands; therefore they are not found suitable to be used in this type of tests [4]. A special device, to research the rolls materials with respect to their resistance against thermal fatigue, is described in the work [9] but its operation frequency is also 0,03 Hz.

Proposal of the test procedure

In the sense of aforesaid thesis it is necessary to valuate the individual influences by constant and other conditions, so that the outcomes can be compared [5]. Hereby proposed procedure is focused on studying cyclical heat stress.

For our experiments we needed to develop a device fulfilling following criteria:

- To cause cyclical heat stress on specimen of tested material within range of 80 to 750 °C with option to regulate it within the mentioned range.
- To have option to chose the frequency of the heat stress up to f = 5 Hz
- To have option to change the heating and cooling times by stable intensity of frequency
- Simplicity, reliability and economic efficiency of the device.

Proposal of the experimentation procedure:

Specimen shall be produced according to image No. 1 by remelting the tested overlay material in the same way as the layer is welded on rolls. (ETN, electroslag weld on, automatically under addition).

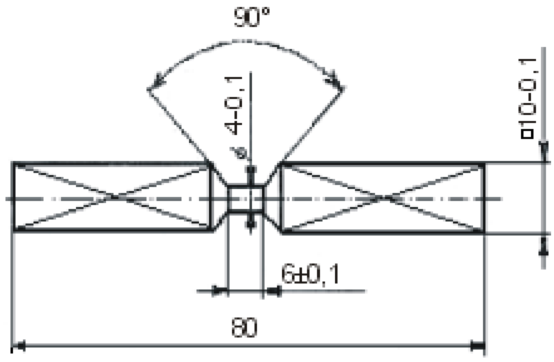


Image No. 1 - Specimen shape

The stress was applied on specimen to find out:

- Critical number of cycles N_F (state A1)
- Development of cracks after the limiting condition A1, their morphology (phase B)
- Intensity of heat stress frequency – its influence on tears (A1) and their development (phase B)
- Cooling speed influence on state A1, on cracks in phase B.

NOTE: By valuating the fractographic description of the fracture processes, the phases are marked with letters and limiting conditions also with numbers [6].

Valuation of the test results:

a) Macroscopic analysis
    - Visual surface analysis
    - Macrofractographic analysis
b) Microscopic analysis
    - Structural analysis
    - Microfractographic analysis
    - Local x- ray microanalysis
    - Diffraction analysis.

Design and preparation of the device, producing cyclical heat stress

For device design marked as CTN (cyklovač tepelného namáhania or DPCHS - Device Producing Cyclical Heat Stress) we have chosen resistance heating and water-cooling. For heating we used (checked by calculation) welding transformer with input power of 33 kVA by 50% load factor.

Electronic device enables control of:

- Frequency of the loading cycle from 25 to 1 Hz.
- Heating time from 0,02 s to 0,5 s (from 1 to 25 periods)
- Pause duration from 0,02 s to 0,5 s (from 1 to 25 periods)
- Heating velocity continuously from 0 to 100% of performance, due to phase shift of the benchmark of the ignitron ignition.

Auxiliary winding on the heating transformer supplies the interrupter of the cooling water feed and the cycle counter.

Cooling is provided by prmanent water streams fed by jets fixed aroun a ring. The water is streaming through holes in the valve which regulates the water, so that while heating the specimen, the waters is falling onto specimen holders and during the cooling period it streams onto heat stressed part of specimen. The valve is controlled by an electromagnet supplied from the auxiliary winding LP, which secures the synchronization of heating and cooling interruptions.

The functional tests on individual constriction joints and the device as such, proved that cyclical heat stress imposed on specimen can run safely even without operator's interventions observing following values:

- Heating time to 750 °C – 0,04 s (2 periods)
- Cooling time to 80 °C – 0,12 s (6 periods).

These values correspond with the cycle frequency f = 6,25 Hz

Application of the device

To verify the device quality, series of tests have been made. For these tests we have chosen overlay materials used by reconstruction of hot working rolls [7, 8]:

- Tool steel 19541,
- Tool steel 19552,
- Alloy type Fe-Cr.

During the tests we were trying to find out the tearing dependence on the number of cycles and on the cycle frequency. We simulated the working conditions of a chosen rolling line with following parameters:

- Maximum temperature 750 °C,
- Minimum temperature 80 °C,
- Frequency f_1 = 5 Hz,
  f_2 = 1 Hz.

Test procedure

Specimen preparation

As initial semi – products we used ingots with dimensions of 62x82x440 mm fabricated by electroslag remelting of weld wires in crystallizer. We have produced specimen from ingots for statistic valuation.

Heat stress in DPCHS / CTN

Due to the performance regulator we set appropriate temperature of heating and cooling. The first tested specimen was loaded by certain number of cycles with frequency f_1. When cracks appeared on the surface the number of cycles was decreased. If no cracks appeared the number was increased. In both cases we continued till the cracks emerged. In this way was stated a probable critical number of cycles for tearing. The concentration was focused on this number of cycles and with help of 3 files of specimen, using a statistic test of X^2 importance, the critical number of cycles N_F was determined.

This procedure was observed by frequency f_2 using the same material. The other tested materials were experimented similar.

Specimen analysis

By detection of surface cracks we used the macroscopic analysis. After purification of the observed parts, The 30 times optically amplified specimen were observed and areas with highest density of cracks were photographed. Images No.2 and No.3 for material Fe- Cr and for material 19 541 are examples of aforementioned analysis.

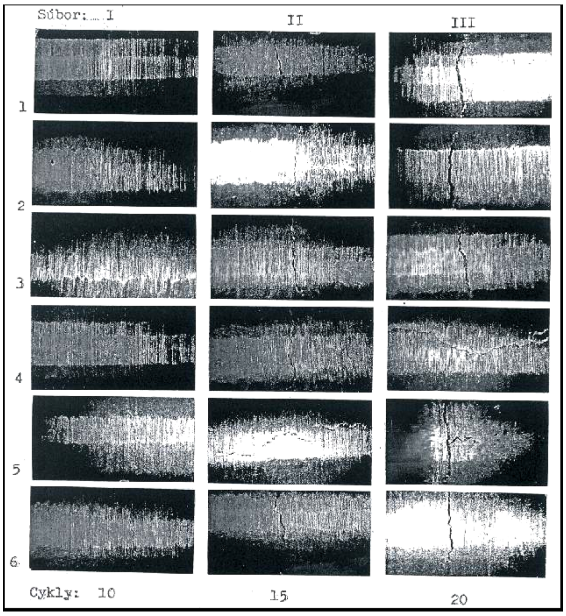


Image No.2 Determination of N statistically for material FCr, f_l = 1Hz

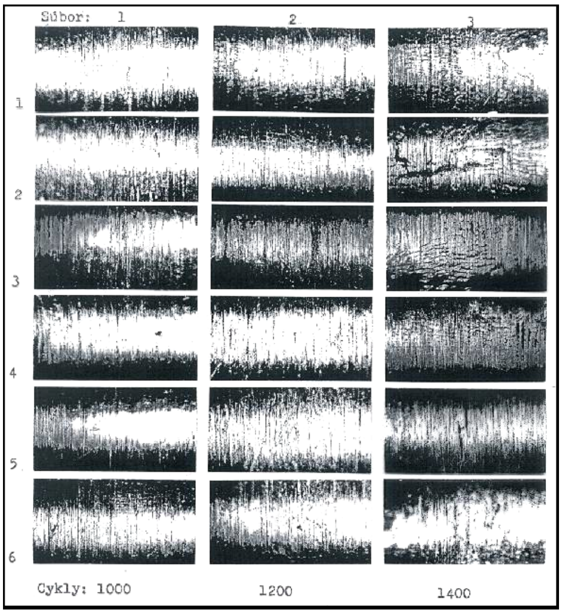


Image No.3 Determination of N statistically for material 19 541, f_l= 5 Hz

Chemical composition of tested materials is described in chart No. 1. Summary of the macroscopic observations is described in chart No. 2.

Material N_F	1		2		3	
	19 541		19 552		FCr	
Chemical composition	wire	overlay	wire	overlay	wire	overlay
C	0,29	0,30	0,35	0,34	5,35	2,55
Mn	0,35	0,37	0,39	0,39	1,15	1,00
Si	0,49	0,36	1,05	0,90	0,73	0,25
Cr	3,18	2,80	4,85	4,55	15,50	11,00
Ni	0,20	0,15	0,15	0,14	1,00	0,65
Mo	3,10	2,85	1,13	0,80	0,55	0,22
V	0,64	0,54	0,50	0,40	-	-

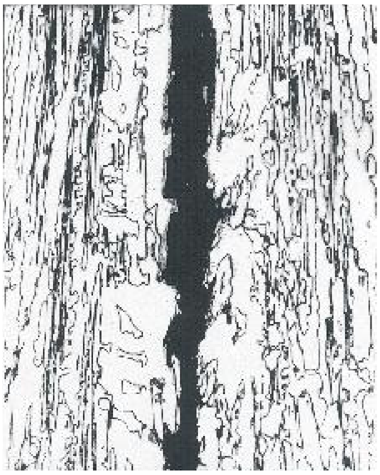
Chart No. 1 – Chemical composition of tested materials

Material	f [Hz]	Number of cycles
1	5	1200
	1	800
2	5	600
	1	500
3	5	under 20
	1	under 10

Chart No. 2 – Results of macroscopic observation

Microscopic analysis clarified the influence of structure, chemical composition and heterogenity on tearing in tested materials. With respect to the purpose of the work – development and verification of the experimental procedure – only material FeCr was chosen out of tested materials for this kind of analysis, because concerning this material there was found the most interesting crack ability and concentration of tears.

As an example we can mention specimen 3 II 3 with remarkable transverse crack. The crash is interdedritically orientated as it can be seen in image No. 4.



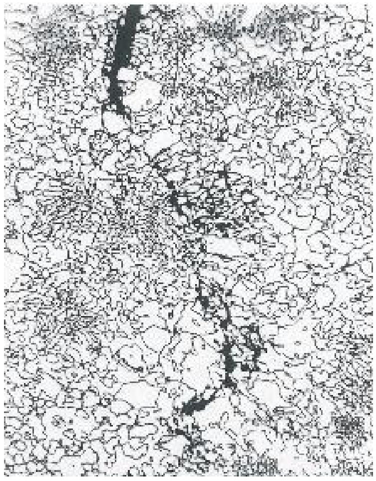
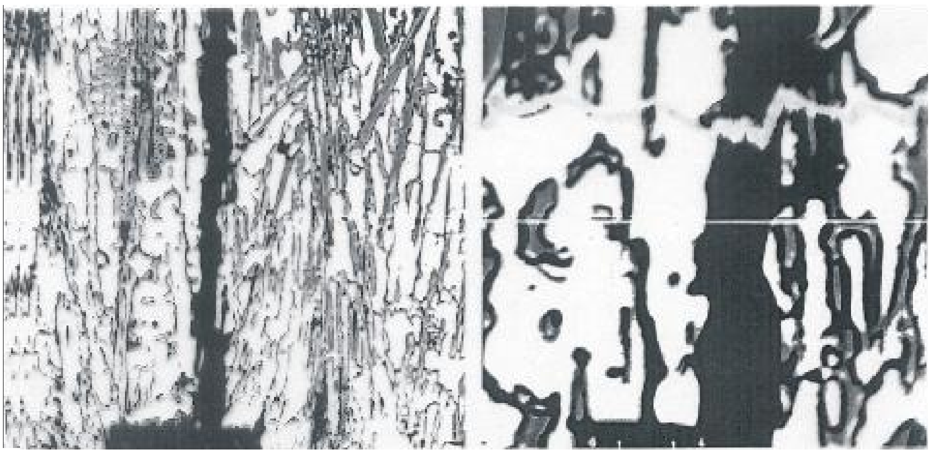


Image No. 4 – Interdendritic orientation of crack in material FCr

Image No. 5 – Dendritic structure of material FCr (100x)

All specimens are two-phase and have significant dendrite morphology. Carbide phase has various dispersion and size of particles. Typical appearance of the FeCr specimen structures is photographically documented in image No. 5. By greater amplification are significant the distinction of dispersion and size of particles of carbide phase. Difference of dispersions is conditioned by selective solidification after continual remelting process.

Image No. 6 – Electron image of chemical composition with line concentration profile



of sulphur specimen with a crack (300x and 1200x)

With individual specimen we were finding out also the microhardness with 0,5 N load. The outcome of measured values is that the hardness of the metal matrix is between 530 and 730 HVM. This hardness spread is natural for cast state and is frought with its heterogenity. Values of microhardness of primary carbides were over 1000 HVM. The hardness of dispersion blend was very distinctive (747 – 1291 HVM) and apparently depends on sizes of particles and dispersion density.

Conclusions of the microscopic analysis

Metalographic specimen analysis proved significant connection between tear orientation and dendritic structure arrangement, whereas the tears have clearly intercrystallic and strain-less character and in the vicinity of cracks and further from them were not found any distinctive values of hardness.

Local x – ray microanalysis served for identification of particles fixed on fracture surface. Selection

of specimen for this type of analysis was motivated by experience gained from structural analysis in a way that a specimen without cracks, with a traverse crack and one with a longitudinal crack should be observed. The results themselves are documented by the electron images of chemical composition and x – ray images of surface. Distribution of atoms of analyzed elements. (S, P, Ni, Fe, Mn, Cr, Mo) To emphasize the presence of sulphur, by cracked specimen we also took photographs of the line concentration profile vertically to the analyzed crack (image No.6).
Summary of the local x – ray microanalysis:
So that the results of the limited number of specimen and measuring can be generalized, we stated that by constant number of heat stress cycles location and shape of cracks are influenced by:

- Chemical heterogenity of material, especially the local concentration of sulphur in interdendritic space of metal;
- By presumption of localizing the tear within range of carbide – metal matrix, we preferred the tear to be expanded into places with higher sulphur content;
- The arrangement, morphology and sulphur bond in the metal matrix.

Summary

The main goal of the work was to propose a procedure of experimental valuation of overlay roll materials. While solving the task we have invented a device for simulation of the cyclical heat stress on specimen of overlay alloys. In comparison with other former devices, our newly designed device is better at simulating frequency of stress, which enables to compare the results with reality.

The proposed procedure was verified on 3 roll overlay materials. Among experiments made on CTN, the most important one provides information about the influence of intensity of heat stress frequency on the critical number of cycles.

The experiments results gained by proposed procedure on CTN device are reproducible and visibly help to shorten and simplify the research works not only in the field of overlay materials for rolls, but also in the field of classification of all cyclically heat stressed materials.

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